# Detection of Supernova Neutrino Collective Oscillations

Cosmic Frontiers Workshop, SLAC, Mar. 2013

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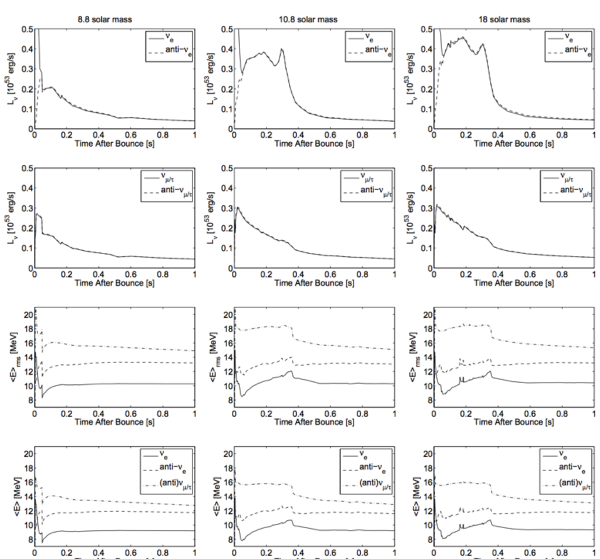
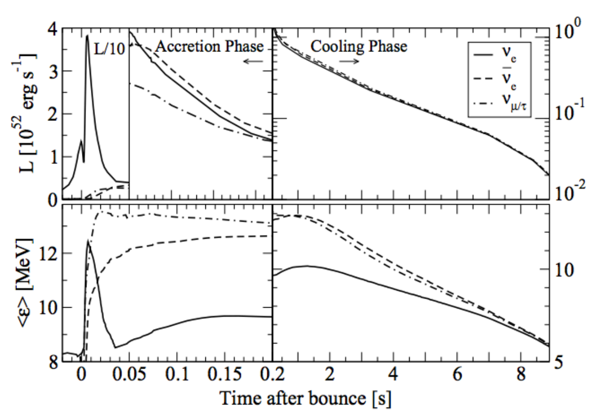
# Neutrino Emission from the PNS

- Because physics in the PNS is a bit of a mystery, there is not good agreement on the neutrino emission.

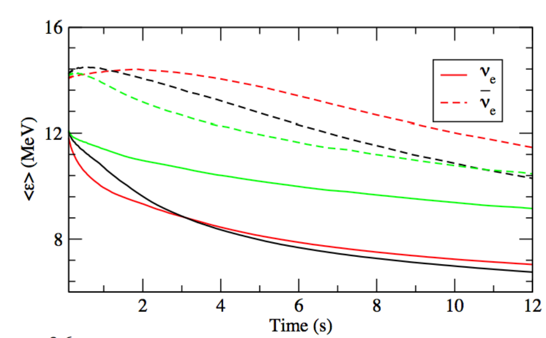
Fischer, et al. (2010)




Hudepohl, et al. (2010)




Roberts, et al. (2012)



# Each group of modelers has their particular strengths

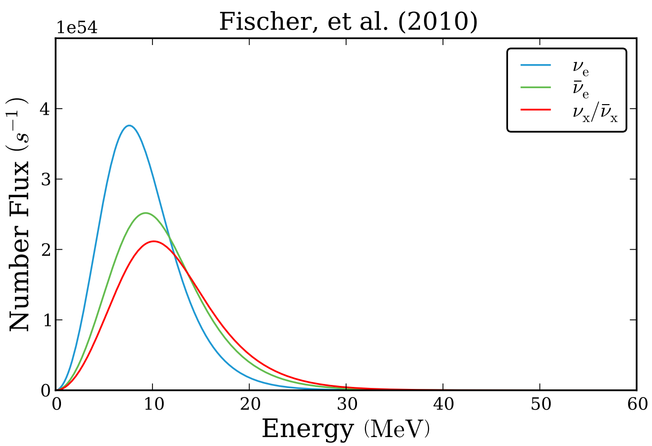
- Fischer, et al. (2010): Full GR radiation transport and hydrodynamics in 1D. Moderately sophisticated neutrino interaction network. Uses standard Shen et al. (1998) EOS for the PNS.

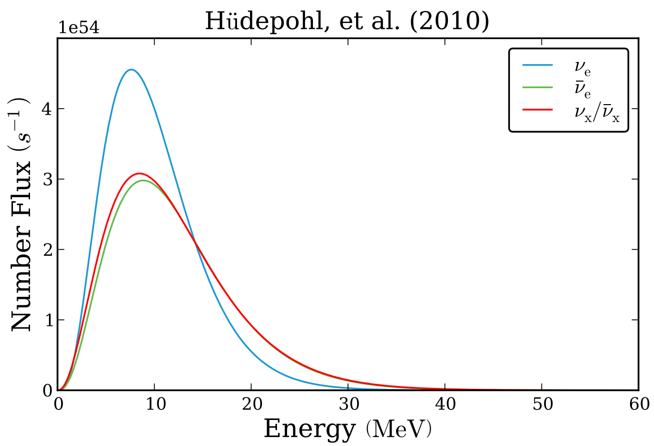
- Hudepohl, et al. (2010): Newtonian radiation transport and hydrodynamics (with corrections) in 1D. Very sophisticated neutrino interaction network. Uses standard Shen et al. (1998) EOS for the PNS.

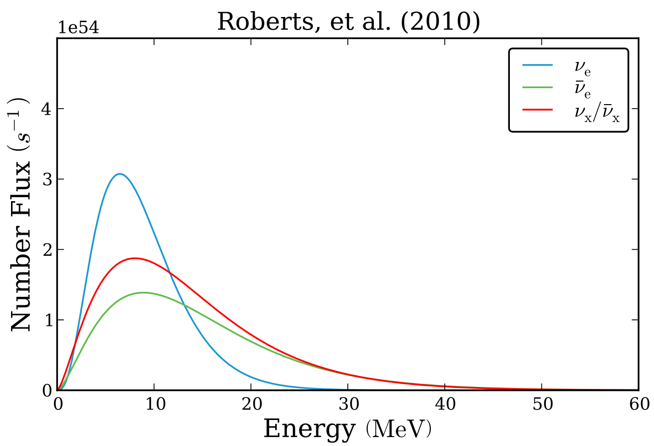
- Roberts, et al. (2012): Full GR radiation transport and hydrodynamics in 1D. Moderately sophisticated neutrino interaction network. Employs cutting edge EOS for PNS, in particular several that are consistent with recent calculations of the nuclear symmetry energy at high density.

# A few typical spectra

## 2s post core bounce




Fischer, et al. (2010)
Classic energy hierarchy
Symmetric late time spectra

Hudepohl, et al. (2010)
Anomalously hot $\bar{\nu}_e's$ .
Symmetric late time spectra

Roberts, et al. (2012)
Anomalously hot $\bar{\nu}_e's$ .
Asymmetric late time spectra

# SNOwGLoBES

- Software tool designed to model neutrino events from core-collapse supernovae in terrestrial neutrino detectors.
- Developed by:


Alex Beck[1], Farzan Beroz[1], Rachel Carr[2], Huaiyu Duan[3], Alex Friedland[4], Nicolas Kaiser[5,1], Jim Kneller[6], Alexander Moss[1], Diane Reitzner[7], Kate Scholberg[1*], David Webber[8], Roger Wendell[1]

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[2] Department of Physics, Columbia University, New York, NY 10027
[3] Department of Physics, University of New Mexico, Albuquerque, NM, 87131
[4] Los Alamos National Laboratory, Los Alamos, NM, 87545
[5] Department of Physics, Karlsruhe Institute of Technology, Germany
[6] Department of Physics, North Carolina State University, Raleigh, NC, 27695
[7] Fermilab, Batavia, IL, 60510-5011
[8] Department of Physics, University of Wisconsin, Madison, WI, 53706-1390
[*] schol@phy.duke.edu

# Event rate calculation only!

- SNoWGLoBES exists for the express purpose of performing this integral:

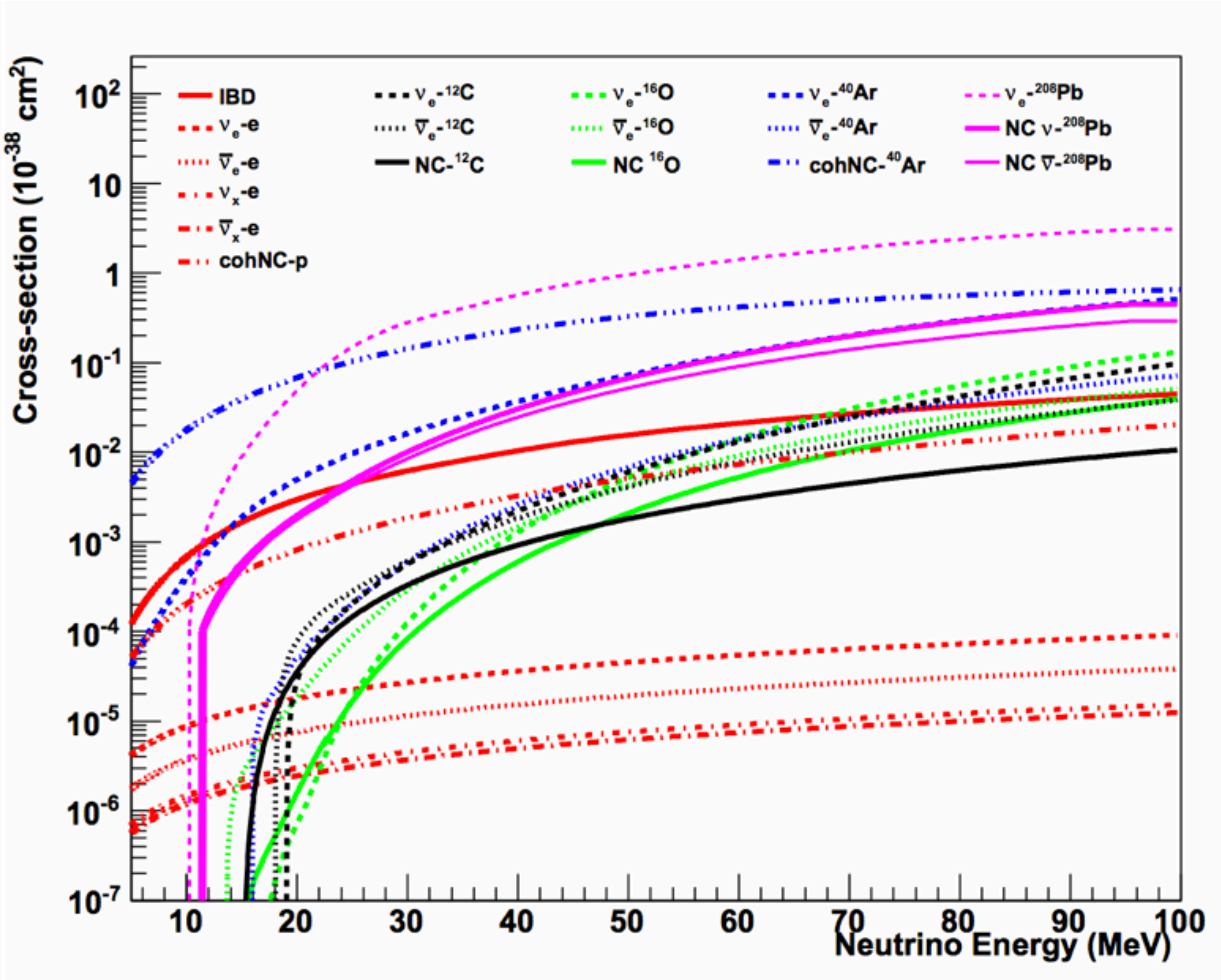
$$\frac{dn}{dE'} = \int_0^\infty \int_0^\infty dE d\hat{E} \Phi(E)\sigma(E)k(E-\hat{E})T(\hat{E})V(\hat{E}-E')$$

- k, T, and V are collected into a single “smearing” matrix.

# Basic set up:

- Assume a distance to a galactic supernova of 10 kpc
- Examine several ‘proxies’ for planned future detectors: 100 kt Water Cherenkov detector, 17kt Liquid Argon detector, 50 kt Liquid Scintillator detector.
- Assume the detectors are buried deep.

# A suite of detection channels




[1] K. Scholberg, Annual Review of Nuclear and Particle Science Vol. 62: 81-103 (2012).

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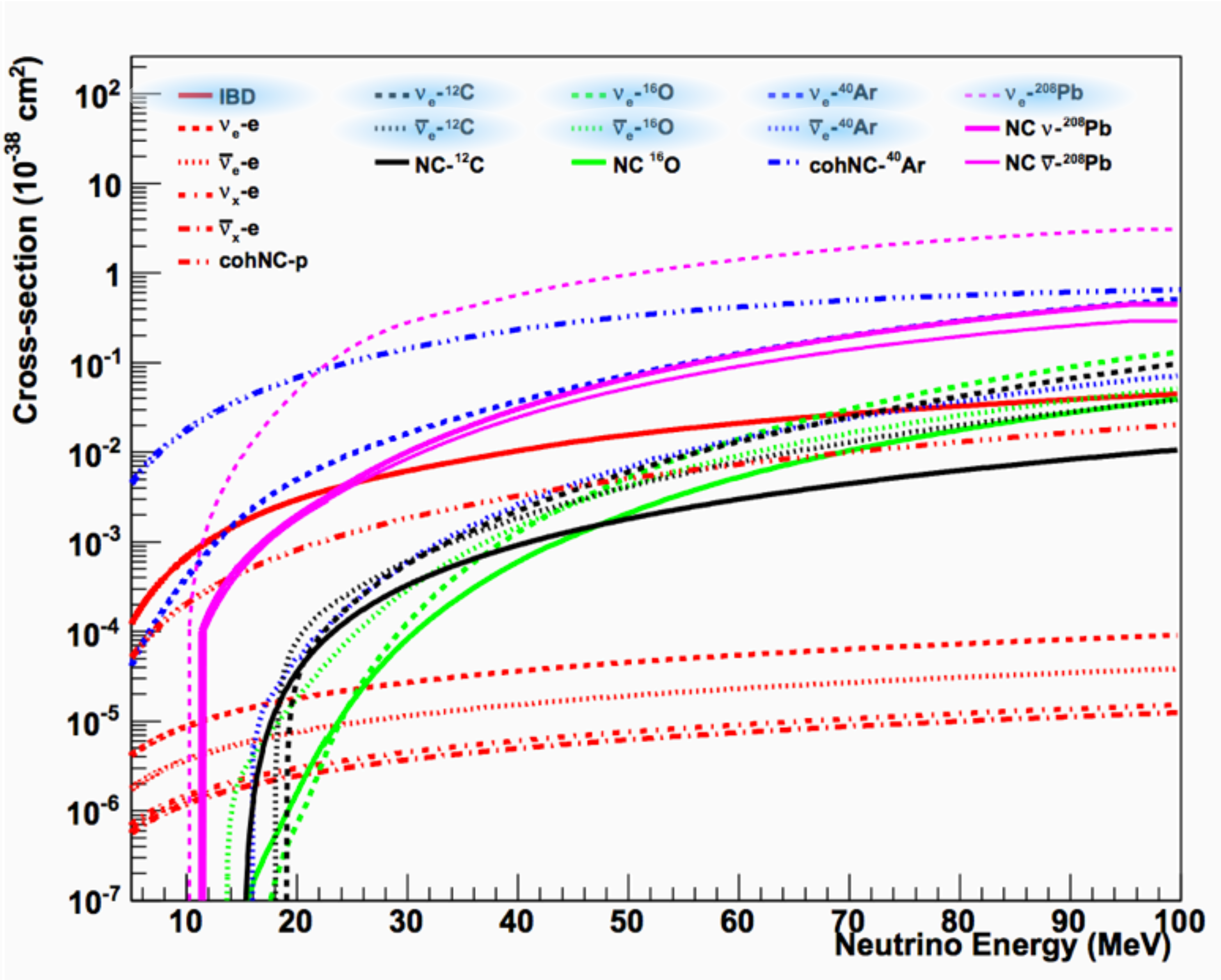



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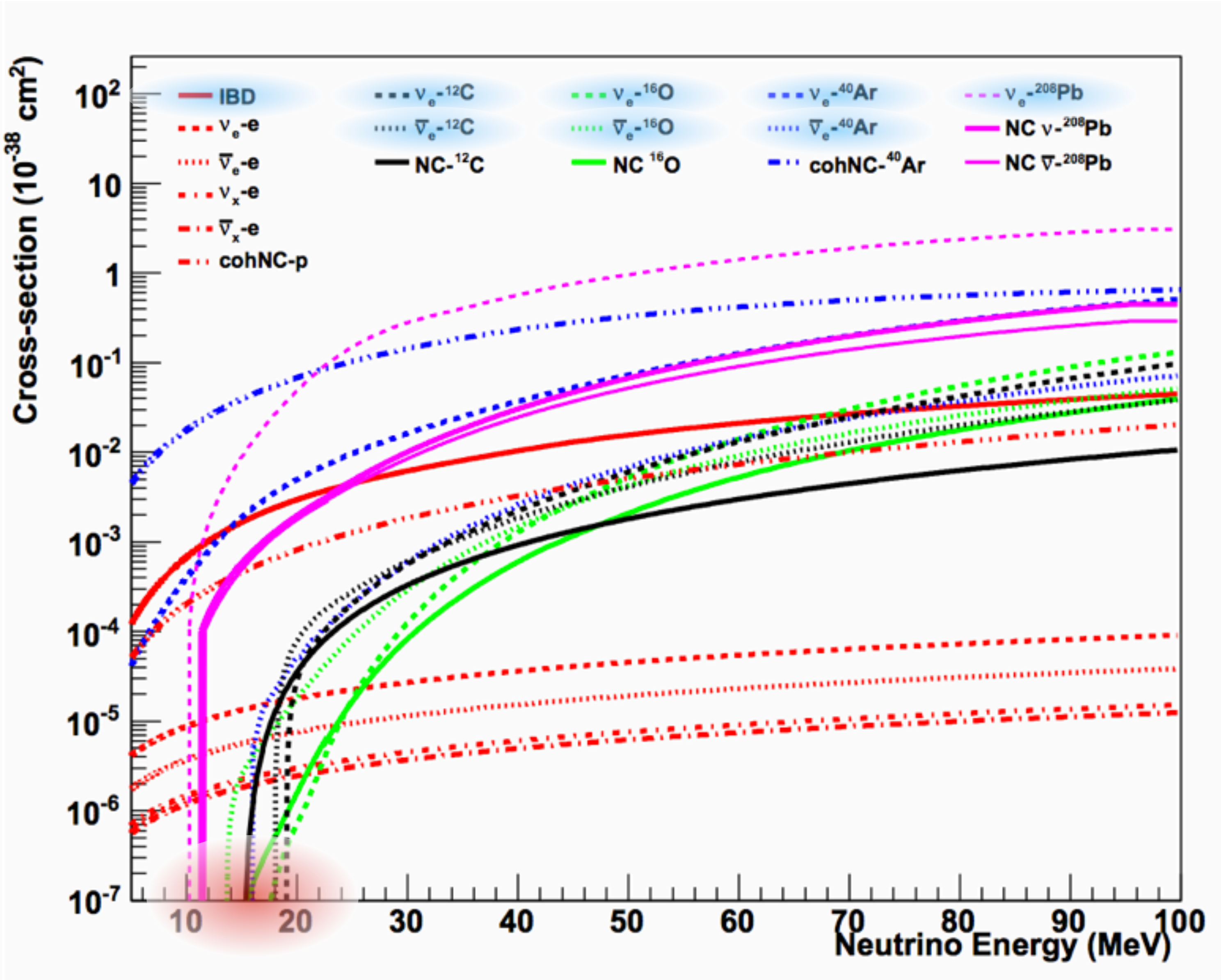


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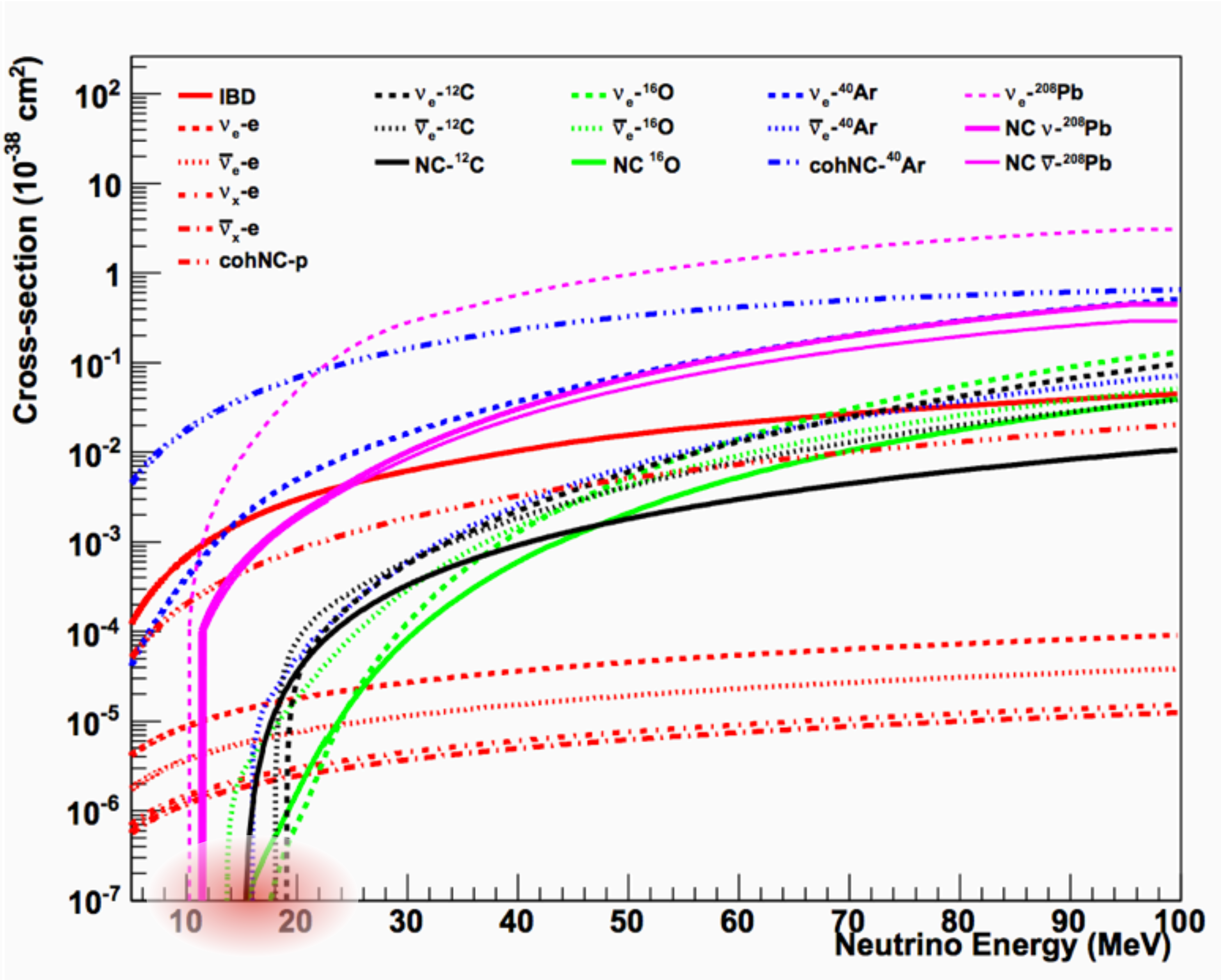


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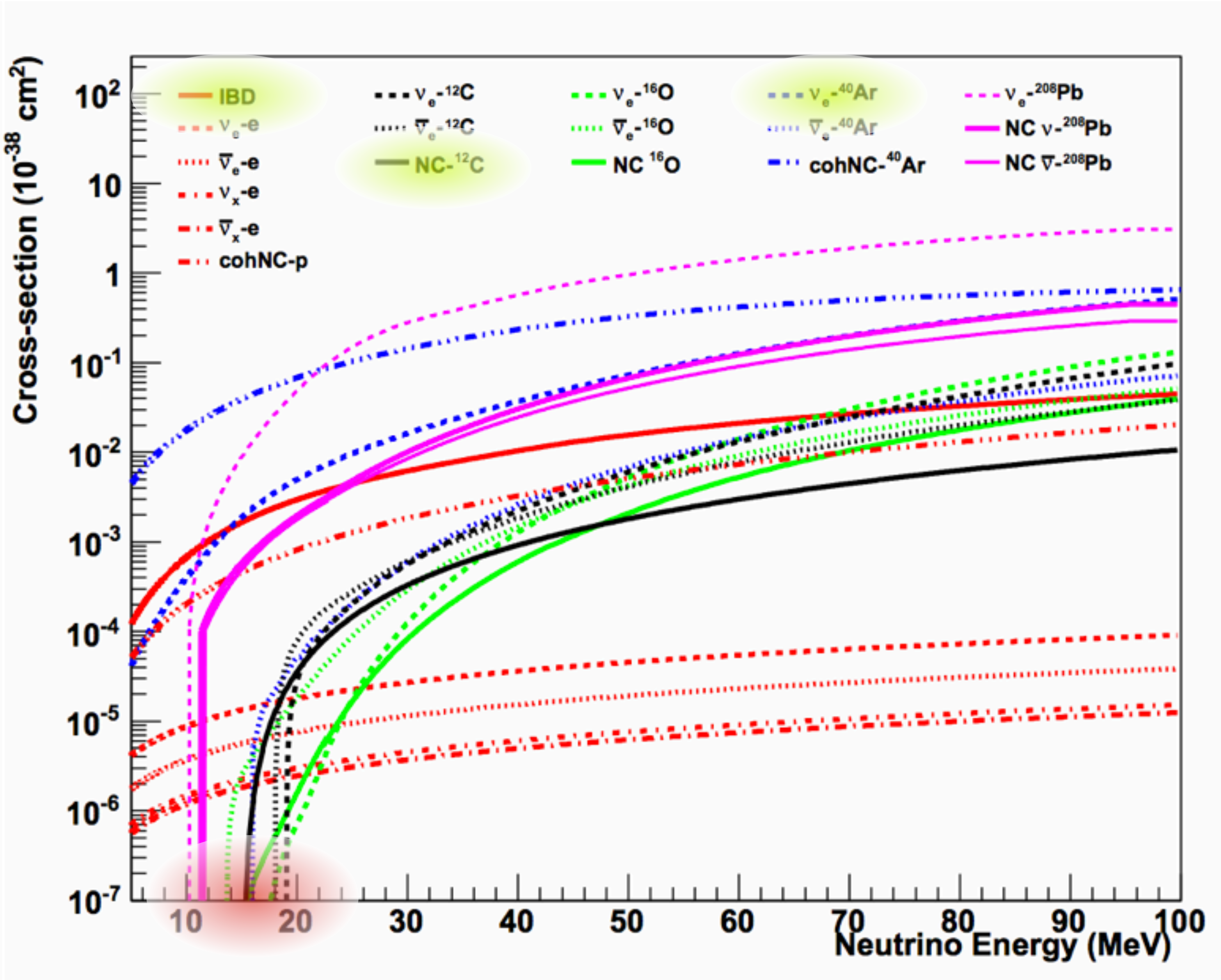


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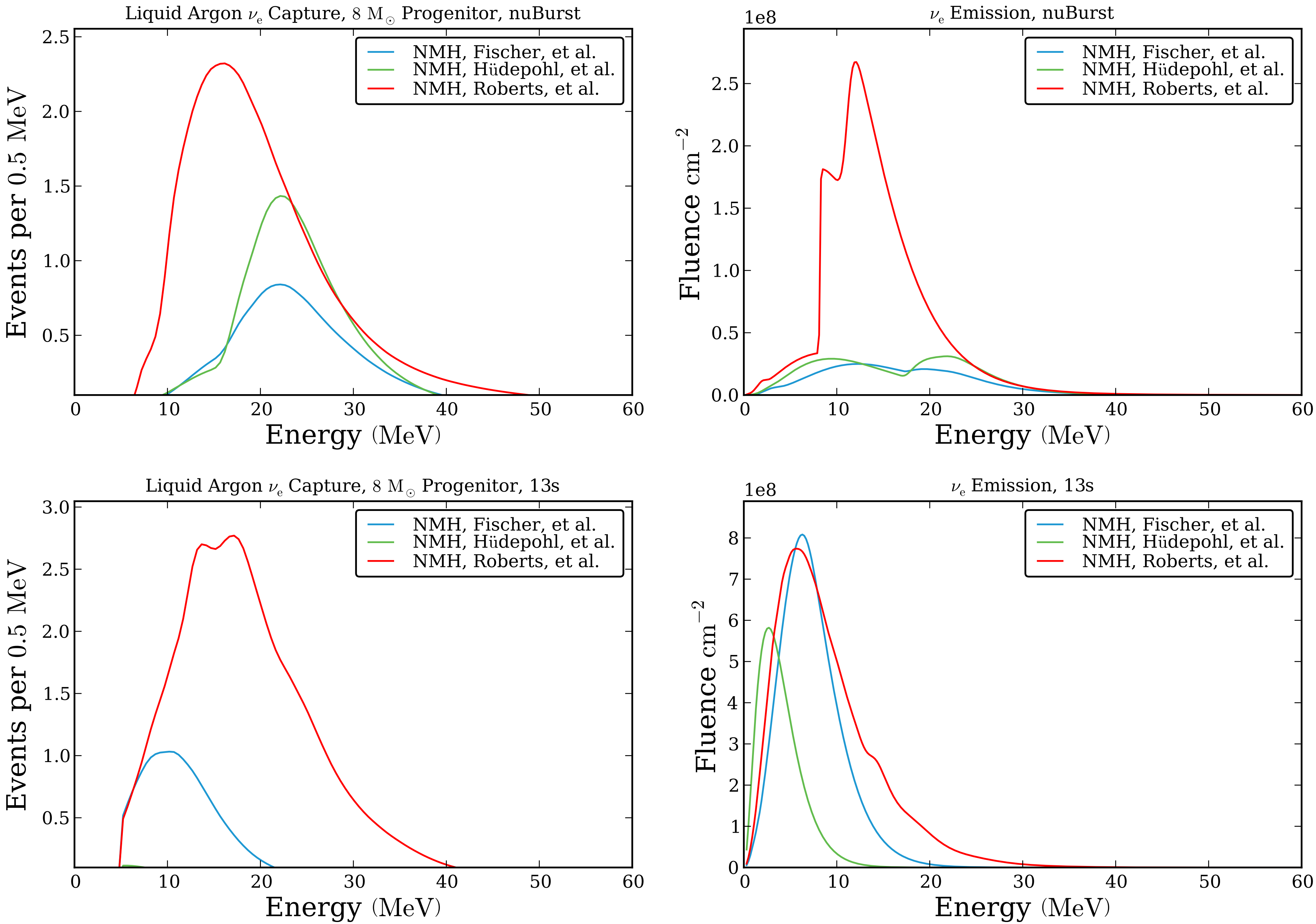
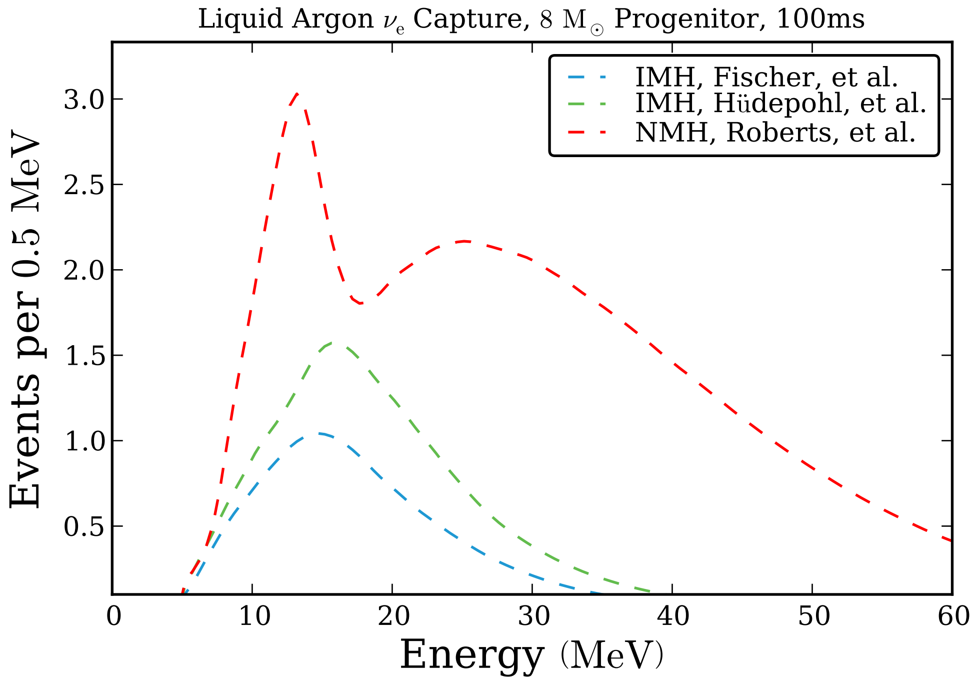
# Signals in Liquid Argon

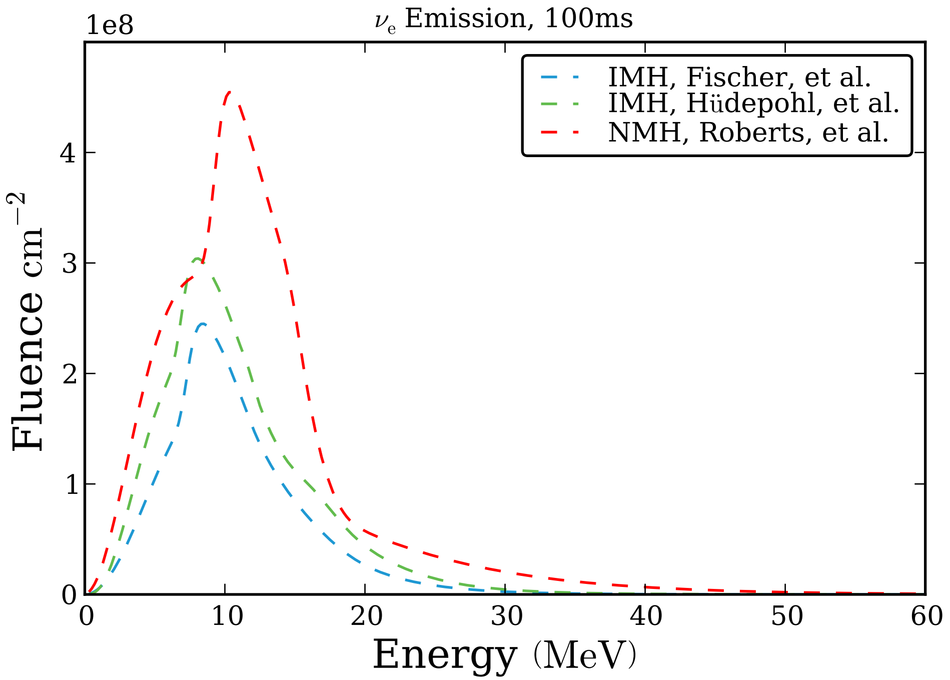
$$\nu_{\mathrm{e}} + {}^{40}Ar \rightarrow e^{-} + {}^{40}K^{*}$$

# Normal mass Hierarchy



# Inverted mass Hierarchy

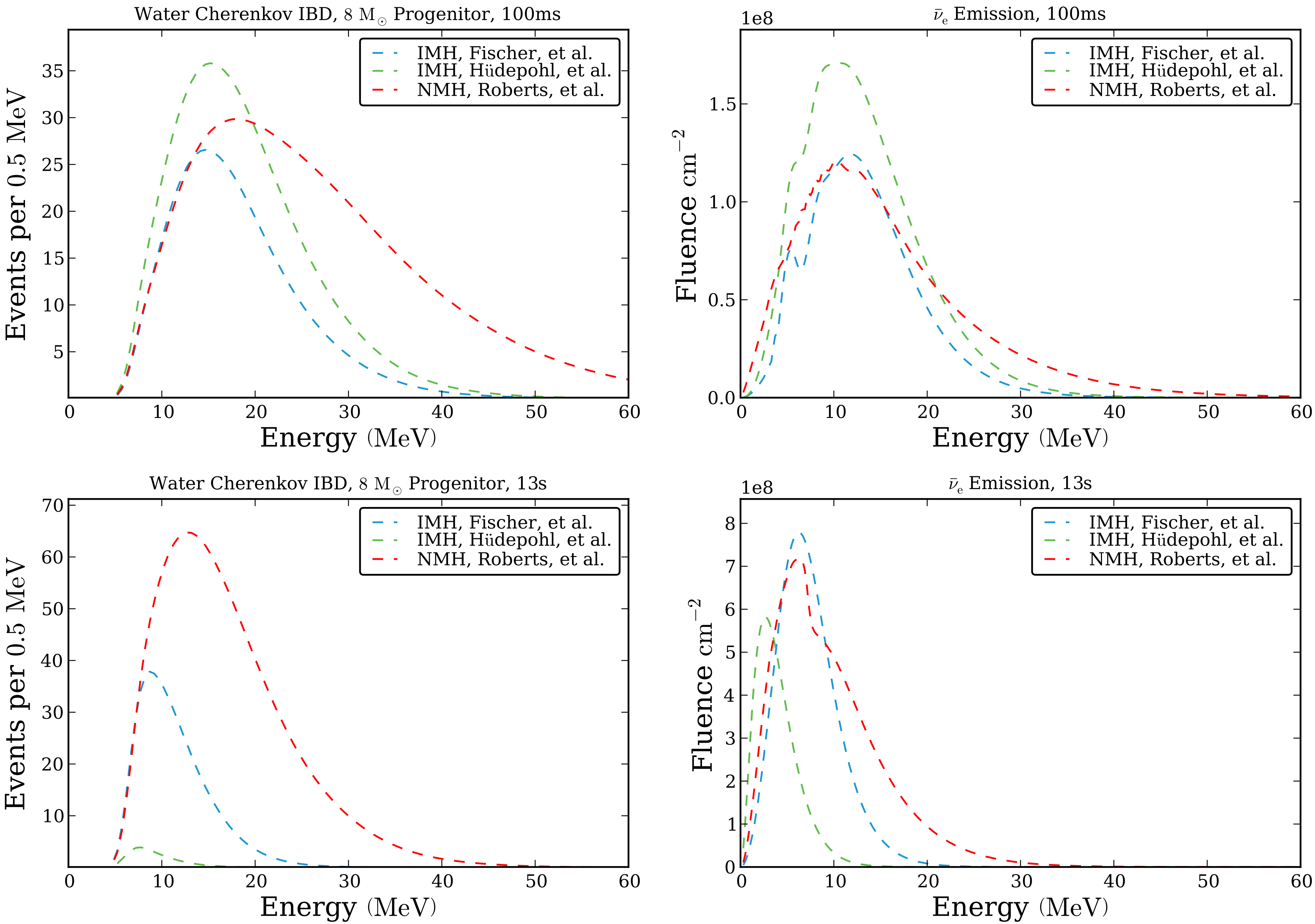


# Signals in Water

$$\bar{\nu}_{\mathrm{e}} + p \rightarrow e^{+} + n$$

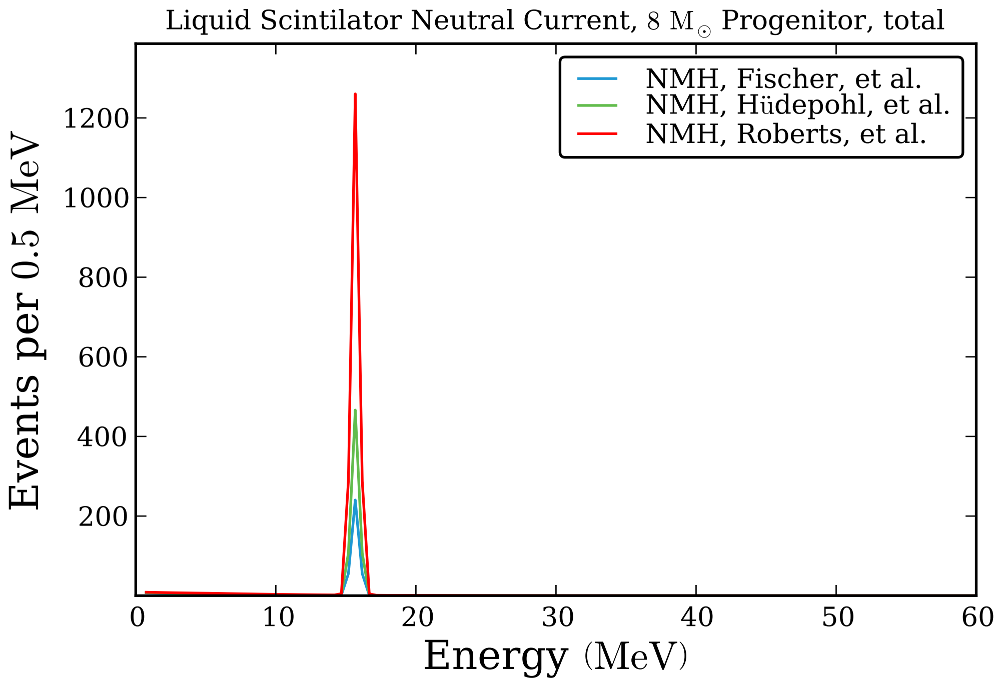
# Inverted mass Hierarchy

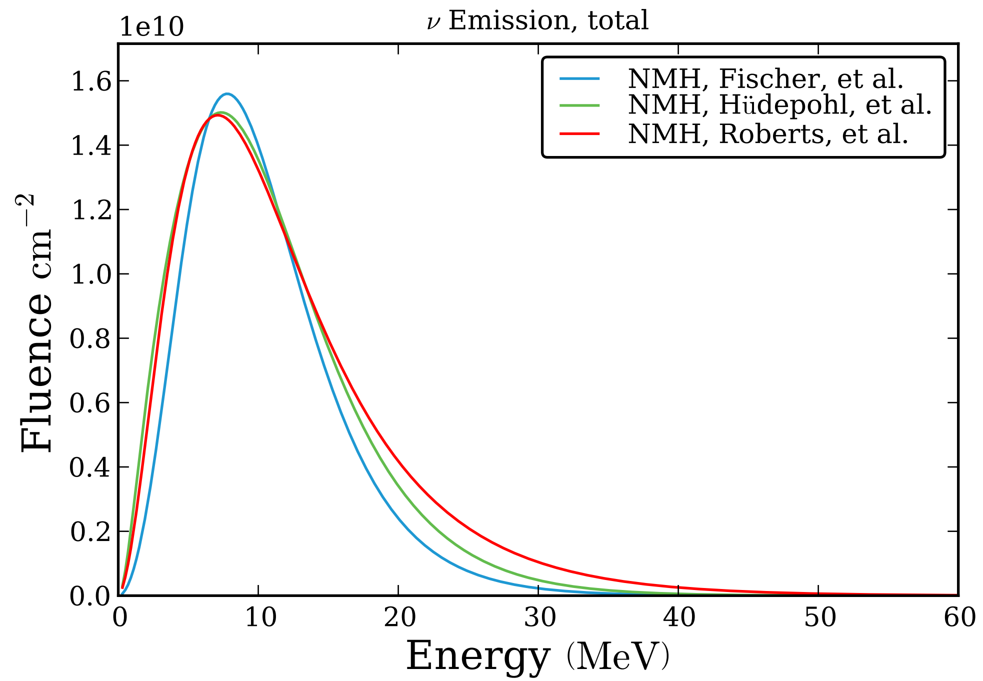


# Signals in Liquid Scintillator

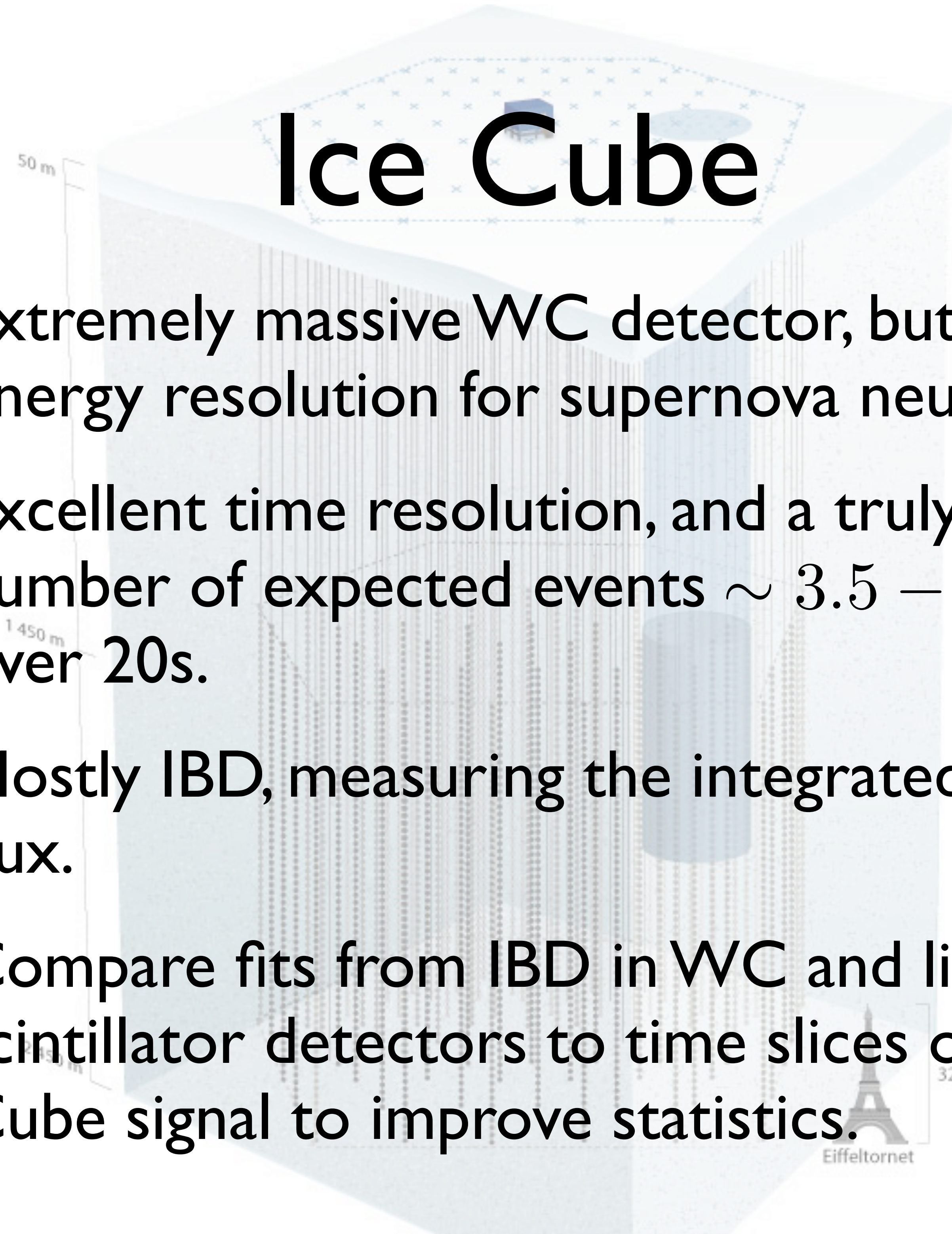
$$\nu + {}^{12}C \rightarrow \nu + {}^{12}C + \gamma$$

# NC interactions with high threshold make excellent neutrino thermometers



# Ice Cube

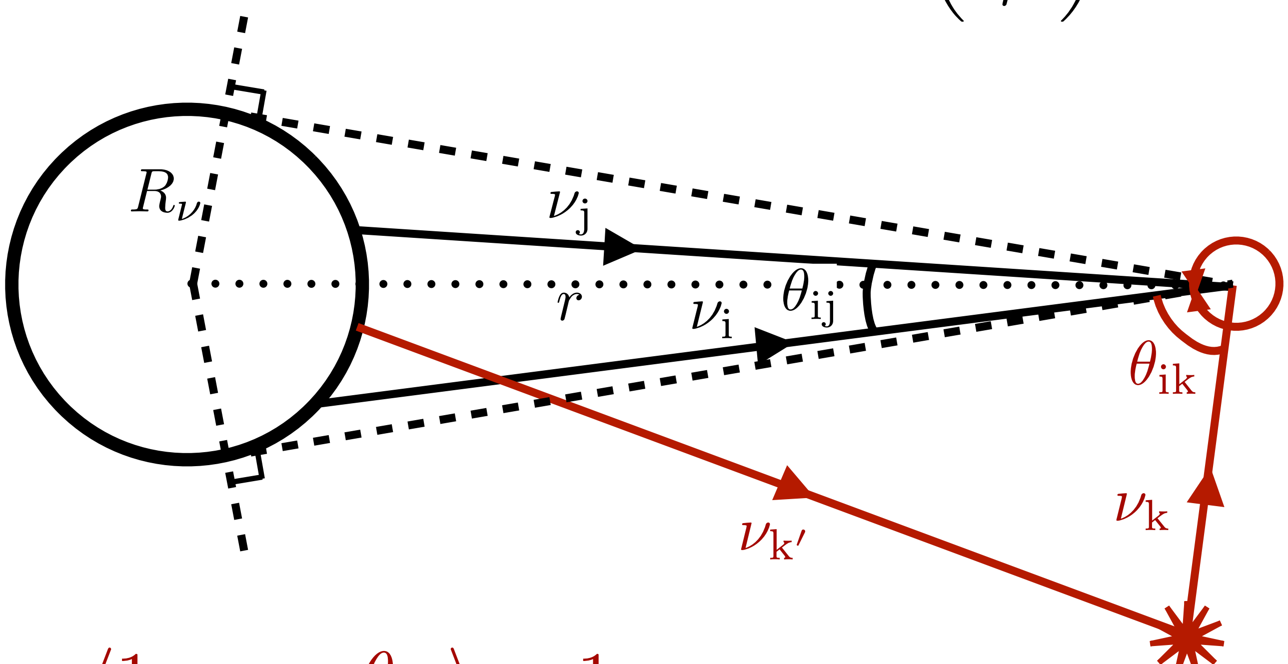



- Extremely massive WC detector, but no energy resolution for supernova neutrinos.
- Excellent time resolution, and a truly titanic number of expected events $\sim 3.5 - 5.3 \times 10^6$ over 20s.
- Mostly IBD, measuring the integrated $\bar{\nu}_{\mathrm{e}}$ flux.
- Compare fits from IBD in WC and liquid scintillator detectors to time slices of the Ice Cube signal to improve statistics.

# Do we fully understand flavor transformation?

J. F. Cherry, A. Friedland, G. M. Fuller, J. Carlson, and A. Vlasenko,
Phys. Rev. Lett. **108**, 261104 (2012), 1203.1607.

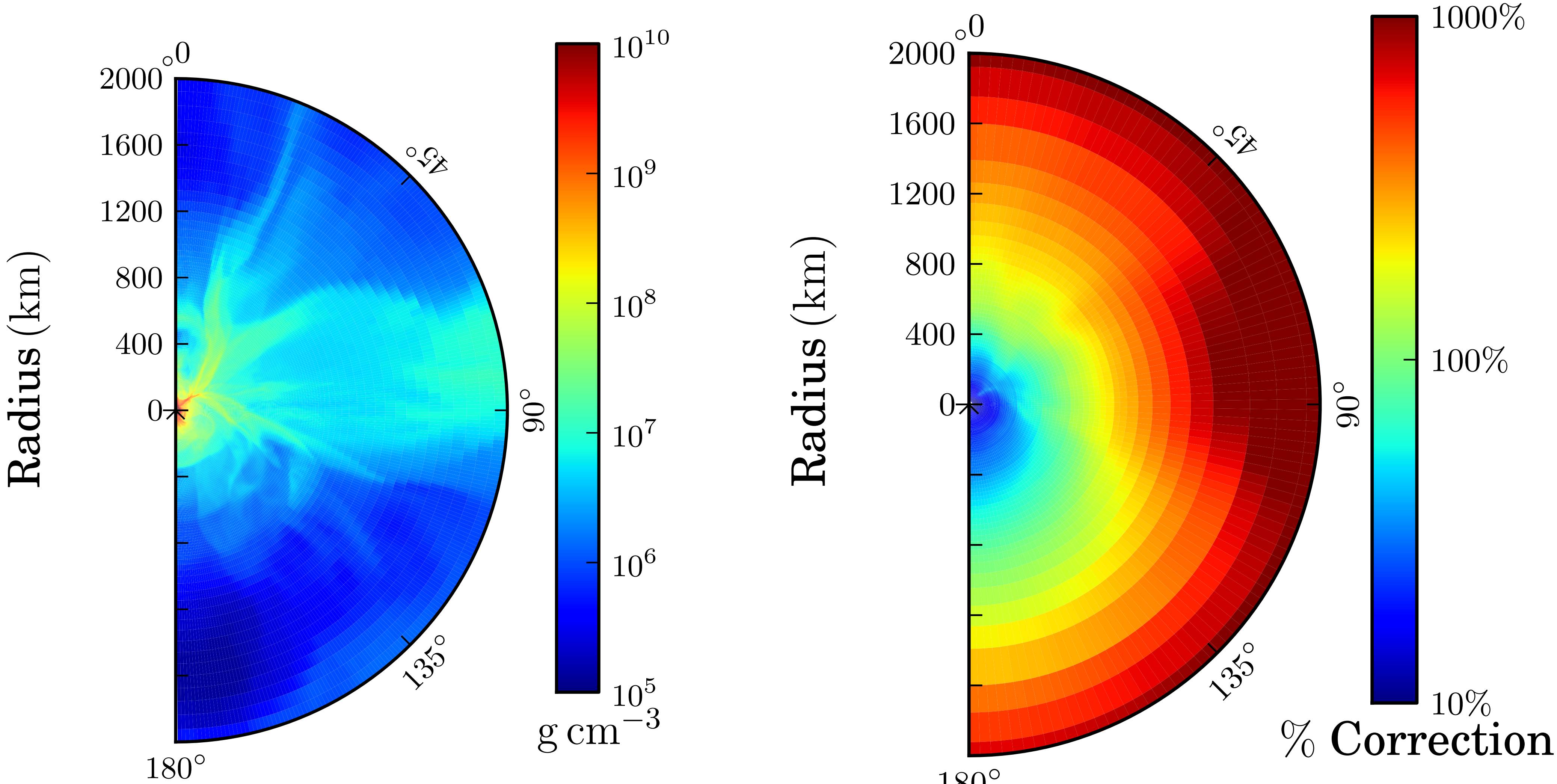
$$r \gg R_\nu \Rightarrow \langle 1 - \cos\theta_{\rm ij} \rangle \propto \left(\frac{R_\nu}{r}\right)^2$$



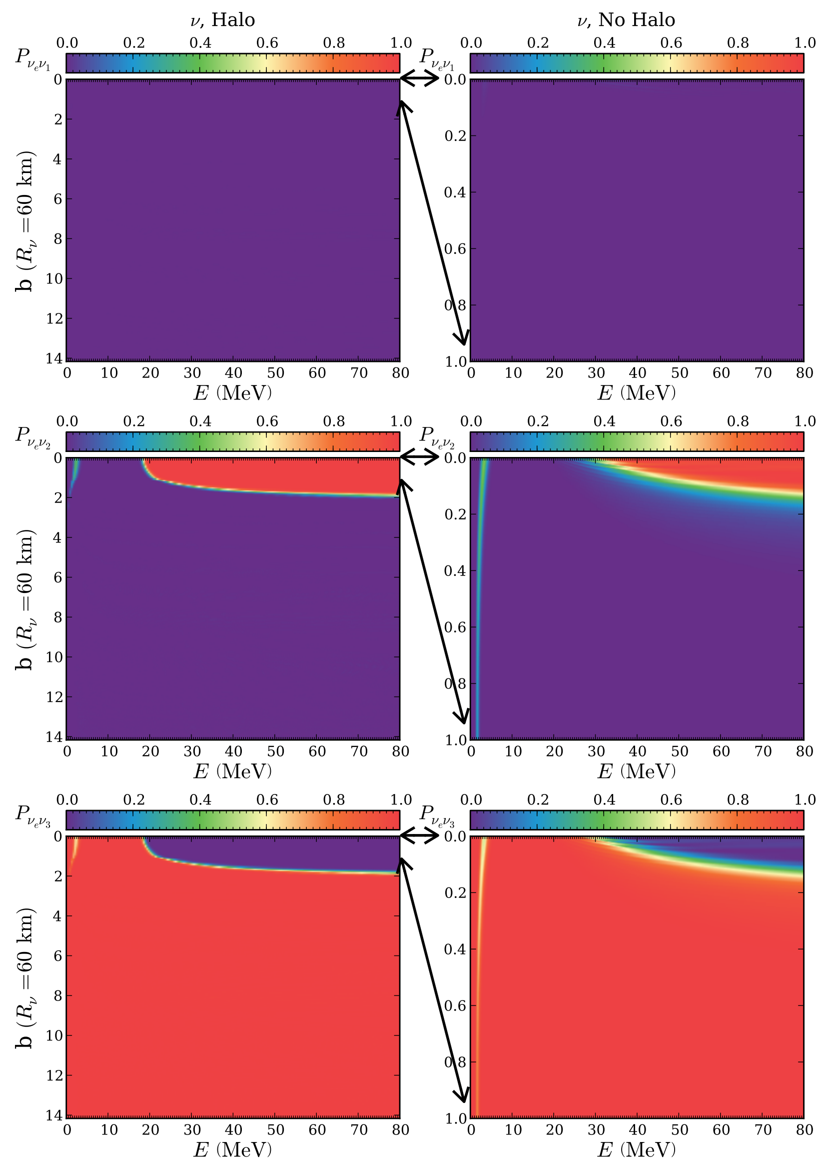

$$\langle 1 - \cos\theta_{\rm ik} \rangle \approx 1$$

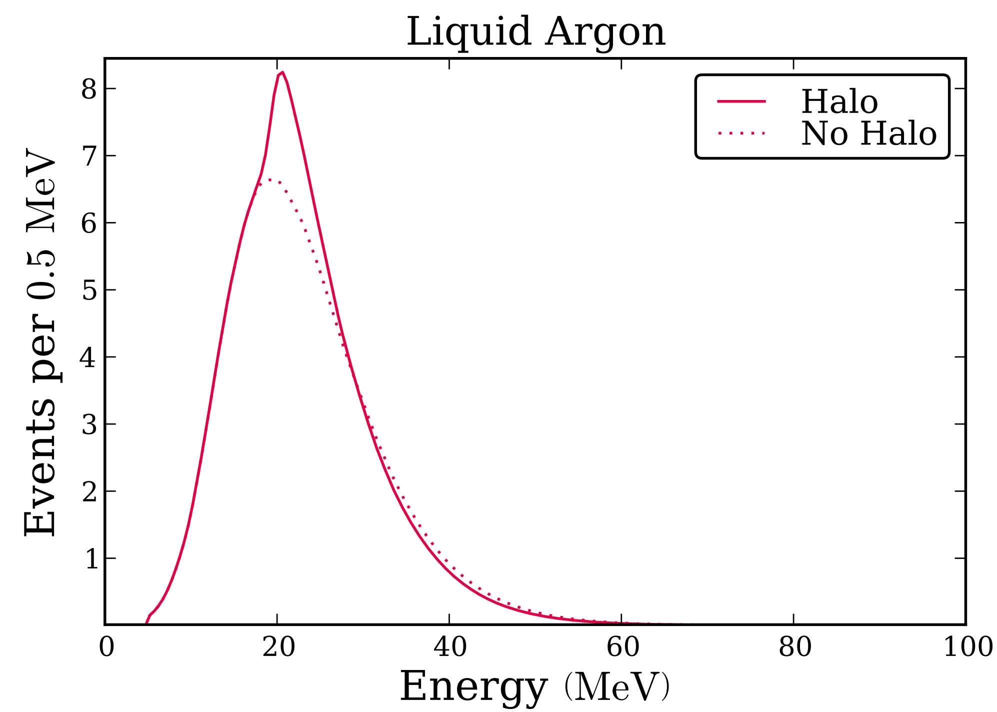
$\sim 10^{-3}$ of all $\nu'$s

# How large is the Halo effect?



# Is there an observable effect?




"Halo Modification of a Supernova Neutronization Neutrino Burst"
Cherry, Carlson, Friedland, Fuller, Vlasenko, arXiv:1302.1159

# Where does all of this leave us?

- Various detector mediums have their own strengths and, taken as an ensemble, will be able to provide a definite detection of a collective oscillation signal.
- Concrete predictions for observed neutrino signals are still beholden to contentious physics.

Thank you very much!

# Coherent Forward Scattering: Neutrino Flavor Evolution

$$\psi_{\nu,\mathrm{i}} = \begin{bmatrix} \text{amplitude to be } \nu_{\mathrm{e}} \\ \text{amplitude to be } \nu_{\mu} \\ \text{amplitude to be } \nu_{\tau} \end{bmatrix}$$

$$i\frac{\partial}{\partial t}\psi_{\nu,\mathrm{i}} = \left(H_{\mathrm{vac,i}} + H_{\mathrm{e,i}} + H_{\nu\nu,\mathrm{i}}\right)\psi_{\nu,\mathrm{i}}$$

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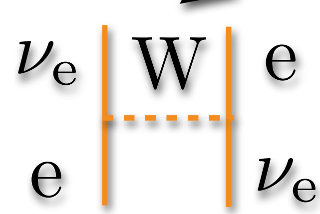
neutrino-electron
charged current
forward exchange
scattering



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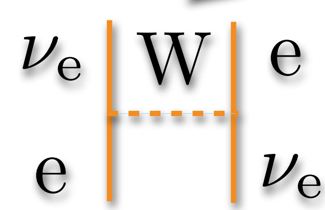
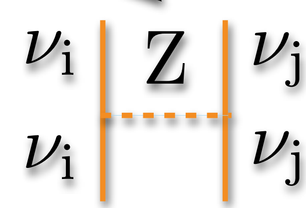
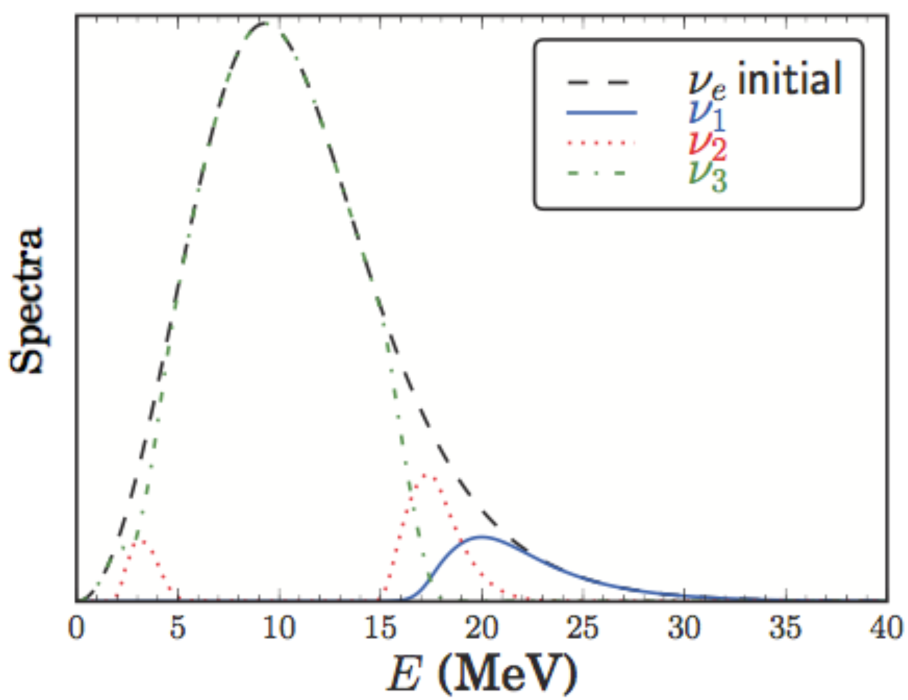



neutrino-neutrino
neutral current
forward scattering

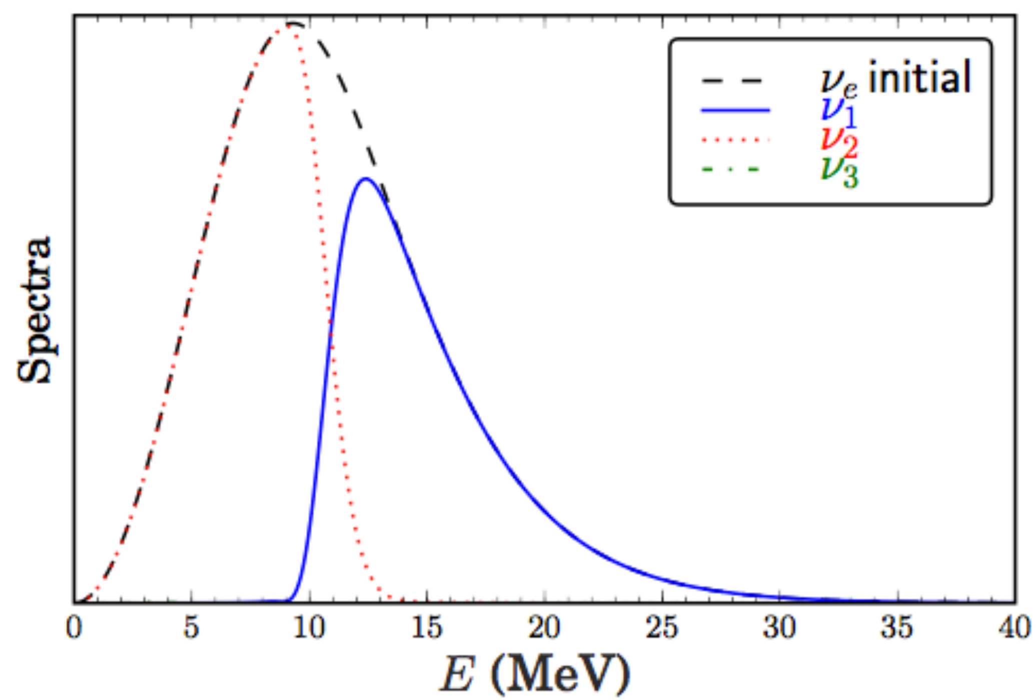


# Determination of Fundamental Mixing Parameters

Normal Neutrino Mass Hierarchy




Inverted Neutrino Mass Hierarchy




J. F. Cherry, G. M. Fuller, J. Carlson, H. Duan, and Y.-Z. Qian, Phys. Rev. D, **82**, 085025 (2010), 1006.2175.

# Where do Flavor Swaps come from?

$$\begin{aligned} i\tfrac{d}{dt}\psi_\nu &= H\psi_\nu \\ &= -\mathbf{H}\cdot\tfrac{\sigma}{2}\psi_\nu \end{aligned}$$

$$\begin{bmatrix} \mathrm{e}^- \\ \nu_\mathrm{e} \end{bmatrix} \quad \begin{bmatrix} \mu/\tau \\ \nu_\mu/\nu_\tau \end{bmatrix} \updownarrow$$

Weak Isospin

$\longleftrightarrow$

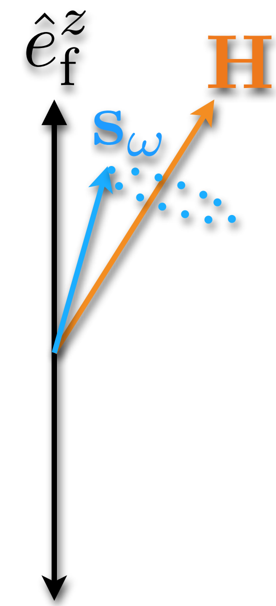
Flavor Isospin

| | $\mathrm{e}^-$ – flavor | $\tau$ – flavor | mixed flavor |
|---|---|---|---|
| $\mathbf{s}_\nu \equiv \psi_\nu^\dagger \dfrac{\sigma}{2}\psi_\nu$ | $\uparrow$ | $\downarrow$ | $\leftrightarrows$ |
| $\mathbf{s}_{\bar\nu} \equiv (\sigma_\mathrm{y}\psi_{\bar\nu})^\dagger \dfrac{\sigma}{2}(\sigma_\mathrm{y}\psi_{\bar\nu})$ | $\downarrow$ | $\uparrow$ | $\leftrightarrows$ |

$$\frac{d}{dt}\mathbf{s} = \mathbf{s}\times\mathbf{H}$$

# How does this help?

$$\frac{d}{dt}\mathbf{s}_\omega = \mathbf{s}_\omega \times \mathbf{H} \qquad \omega = \pm\frac{\Delta m^2}{2E_\nu}$$



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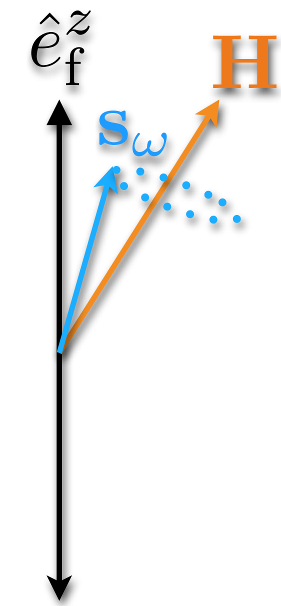
$$\frac{d}{dt}\mathbf{s}_\omega = \mathbf{s}_\omega \times \mathbf{H} \qquad\qquad \omega = \pm\frac{\Delta m^2}{2E_\nu}$$

This is just a spin in a magnetic field.



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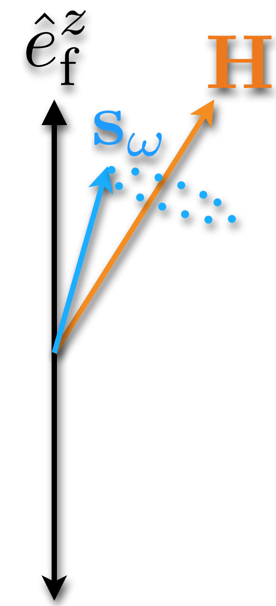



$$\frac{d}{dt}\mathbf{s}_\omega = \mathbf{s}_\omega \times \mathbf{H} \qquad \omega = \pm\frac{\Delta m^2}{2E_\nu}$$

This is just a spin in a magnetic field.

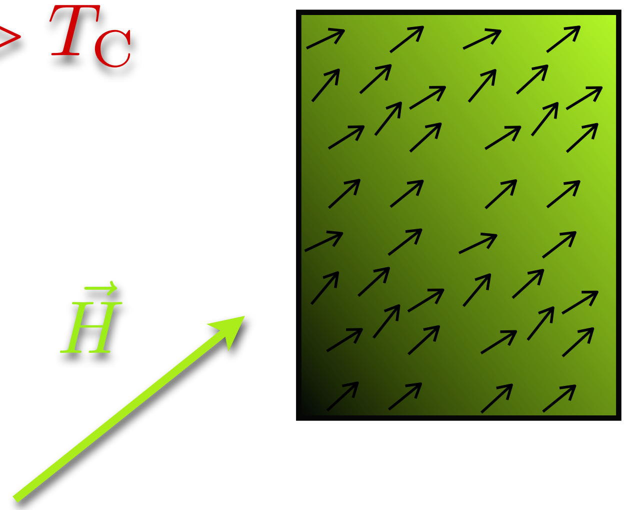
$$\frac{d}{dt}\mathbf{s}_\omega = \mathbf{s}_\omega \times \left(\omega\mathbf{H}_{\mathrm{v}} + \mathbf{H}_{\mathrm{e}} + \mathbf{H}_{\nu\nu}\right)$$

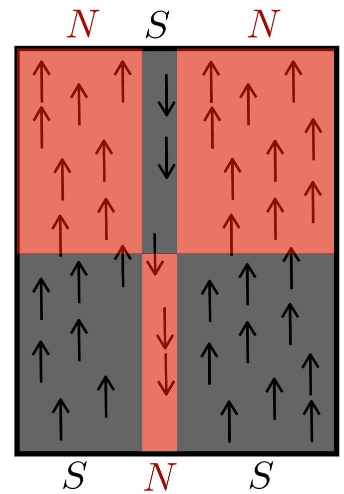
$$\mathbf{H}_{\nu\nu} = -\mu\left(r\right)\int_{-\infty}^{\infty} f\left(\omega'\right)\mathbf{s}_{\omega'}d\omega'$$

$$T = \frac{1}{2\mu\left(r\right)}\left|\mathbf{H}_{\nu\nu}\right|^2 \qquad U = \frac{\omega_{\mathrm{sync}}}{dil\left(r\right)}\mathbf{H}_{\mathrm{v}}\cdot\int_{-\infty}^{\infty} f\left(\omega'\right)\mathbf{s}_{\omega'}d\omega'$$

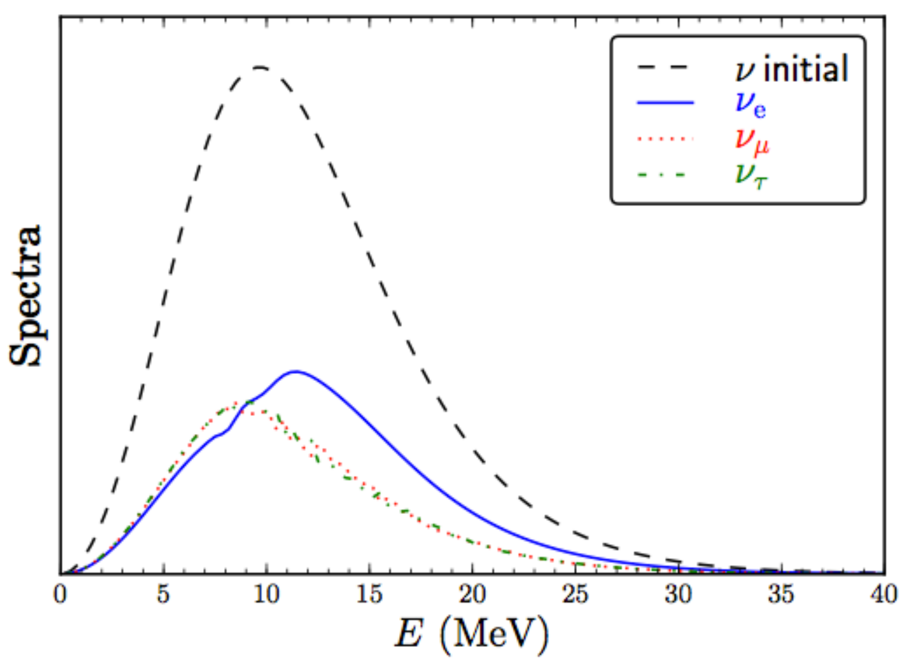
# Magnetic Analogy

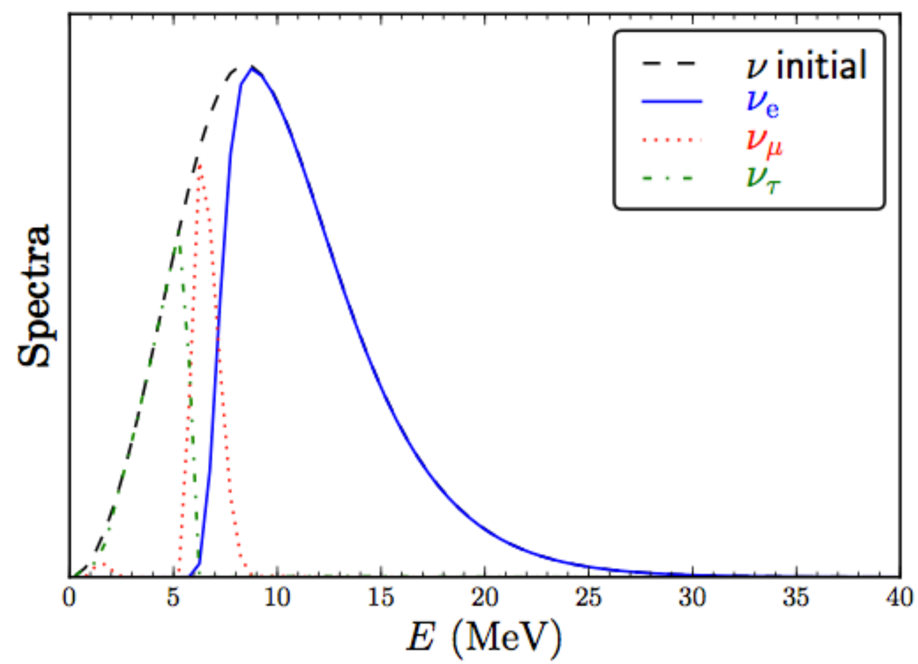
$T > T_C$




$T < T_C$



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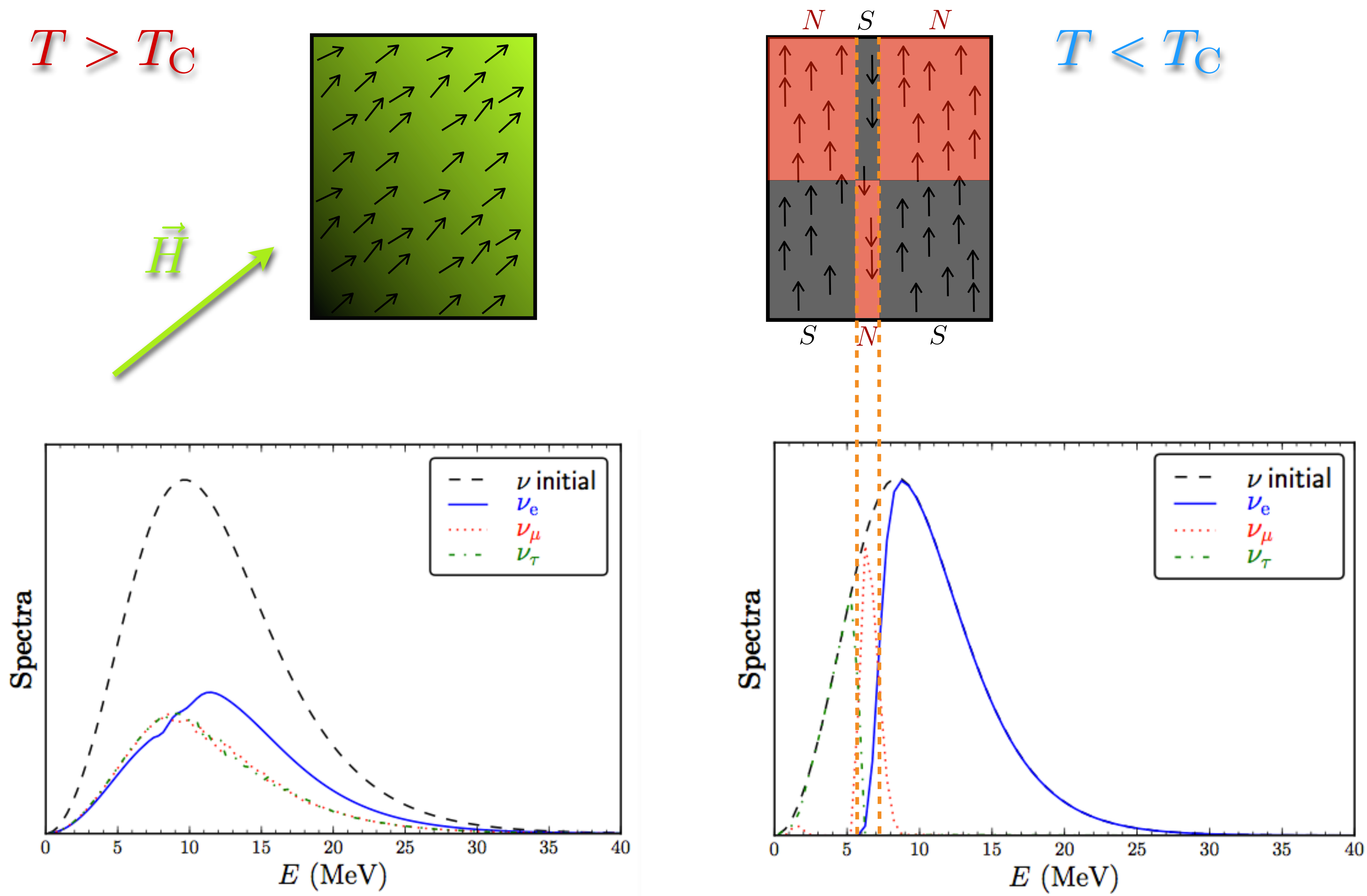

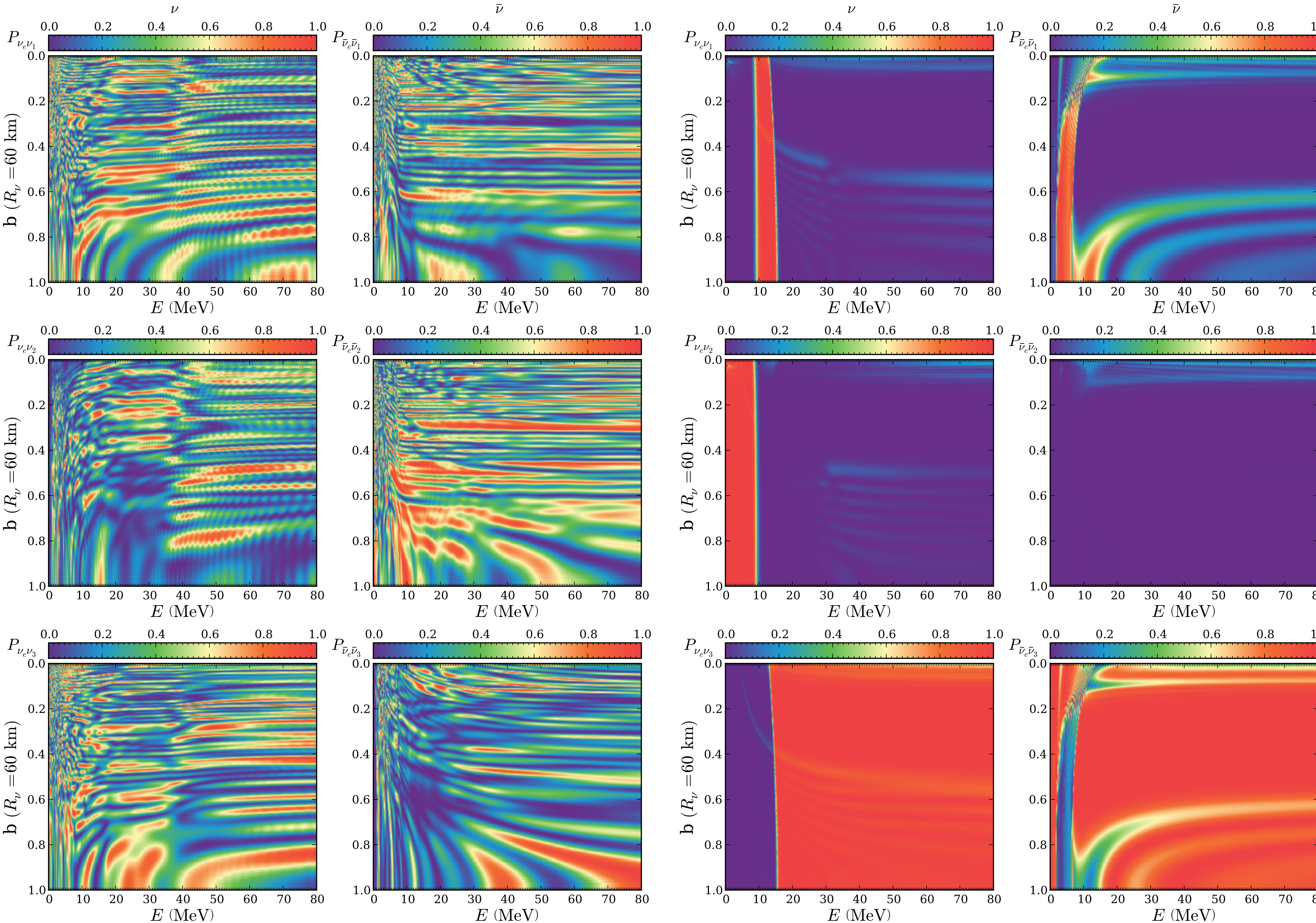

ν
ν̄
ν
ν̄
$P_{\nu_e\nu_1}$
$P_{\bar{\nu}_e\bar{\nu}_1}$
$P_{\nu_e\nu_1}$
$P_{\bar{\nu}_e\bar{\nu}_1}$
$P_{\nu_e\nu_2}$
$P_{\bar{\nu}_e\bar{\nu}_2}$
$P_{\nu_e\nu_2}$
$P_{\bar{\nu}_e\bar{\nu}_2}$
$P_{\nu_e\nu_3}$
$P_{\bar{\nu}_e\bar{\nu}_3}$
$P_{\nu_e\nu_3}$
$P_{\bar{\nu}_e\bar{\nu}_3}$
0.0 0.2 0.4 0.6 0.8 1.0
b ($R_\nu$ =60 km)
0 10 20 30 40 50 60 70 80
$E$ (MeV)